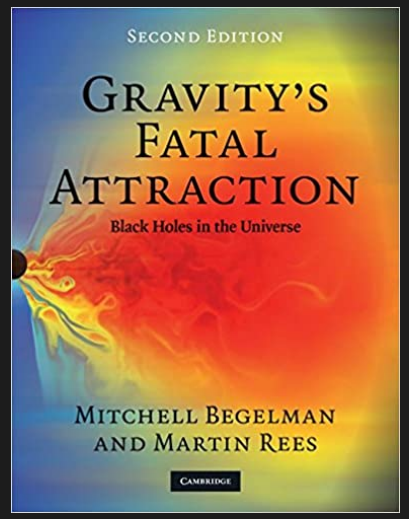
7: Total Eclipse

Physics 17: Black Holes and Extreme Astrophysics

Goals

- Explore the first discovery of an astrophysical black hole
- Find out how matter accretes onto black holes
- Discover how black holes can power some of the brightest objects we see in the Universe

Reading

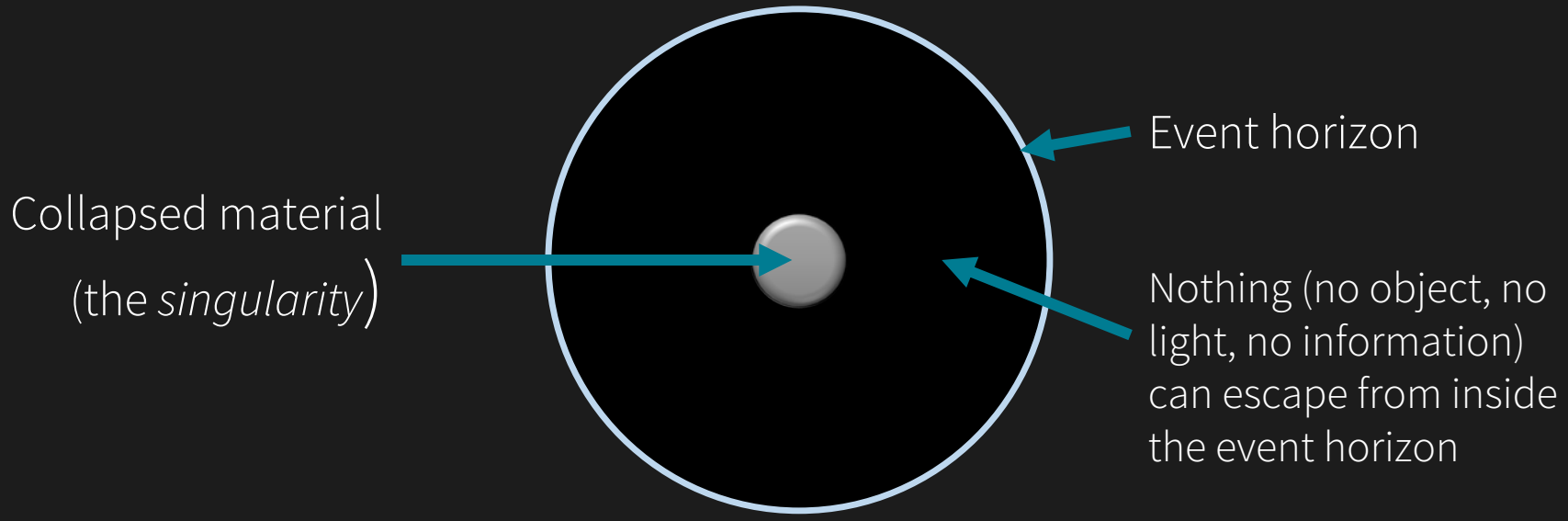


Begelman & Rees

- Chapter 3: Discovery of black holes (p52-58, 65-69)

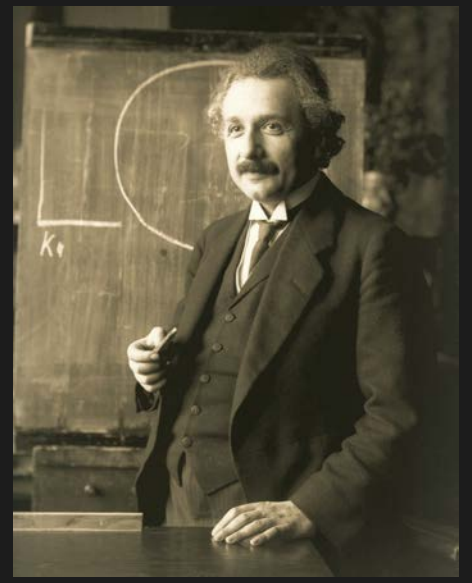
Black Holes

- The escape velocity from $r < \frac{2GM}{c^2}$ (the Schwarzschild radius) exceeds the speed of light
- Nothing can travel faster than the speed of light
- A black hole is an object that has collapsed to within its Schwarzschild radius
- The event horizon $r_H = \frac{2GM}{c^2}$ is the point of no return. Within this radius, gravity is so strong that nothing, not even light, can escape


Collapsed material
(the *singularity*)
Event horizon
Nothing (no object, no light, no information) can escape from inside the event horizon

Too strange to be true!

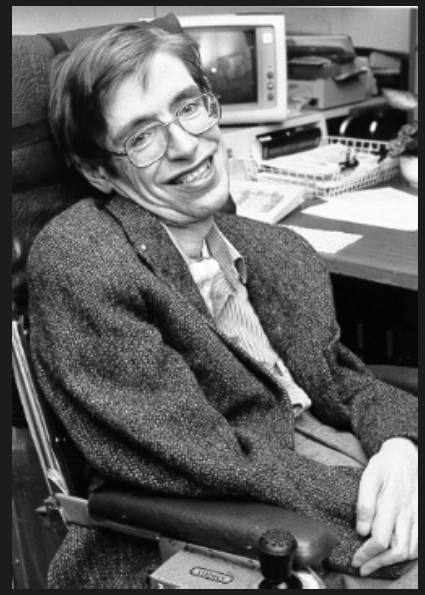
- First ideas of dark stars – Michell & Laplace (1783-96)
- Black holes definitively predicted and described by General Relativity – Einstein's theory of gravity (1916) – coming up in later lectures
- Many scientists believed they were too strange to be true, including Einstein, Eddington (stars can't be allowed to seal themselves off from the Universe when they collapse), Hawking, Wheeler
- Something must save the star from collapsing completely — maybe it spins faster as it collapses, supporting it, or maybe quantum mechanics saves it
- Need to find evidence for black holes in the Universe!



Albert Einstein

Arthur Eddington

John Wheeler



Stephen Hawking

The Nobel Prize in Physics 2020

Roger Penrose

"for the discovery that black hole formation is a robust prediction of general relativity"

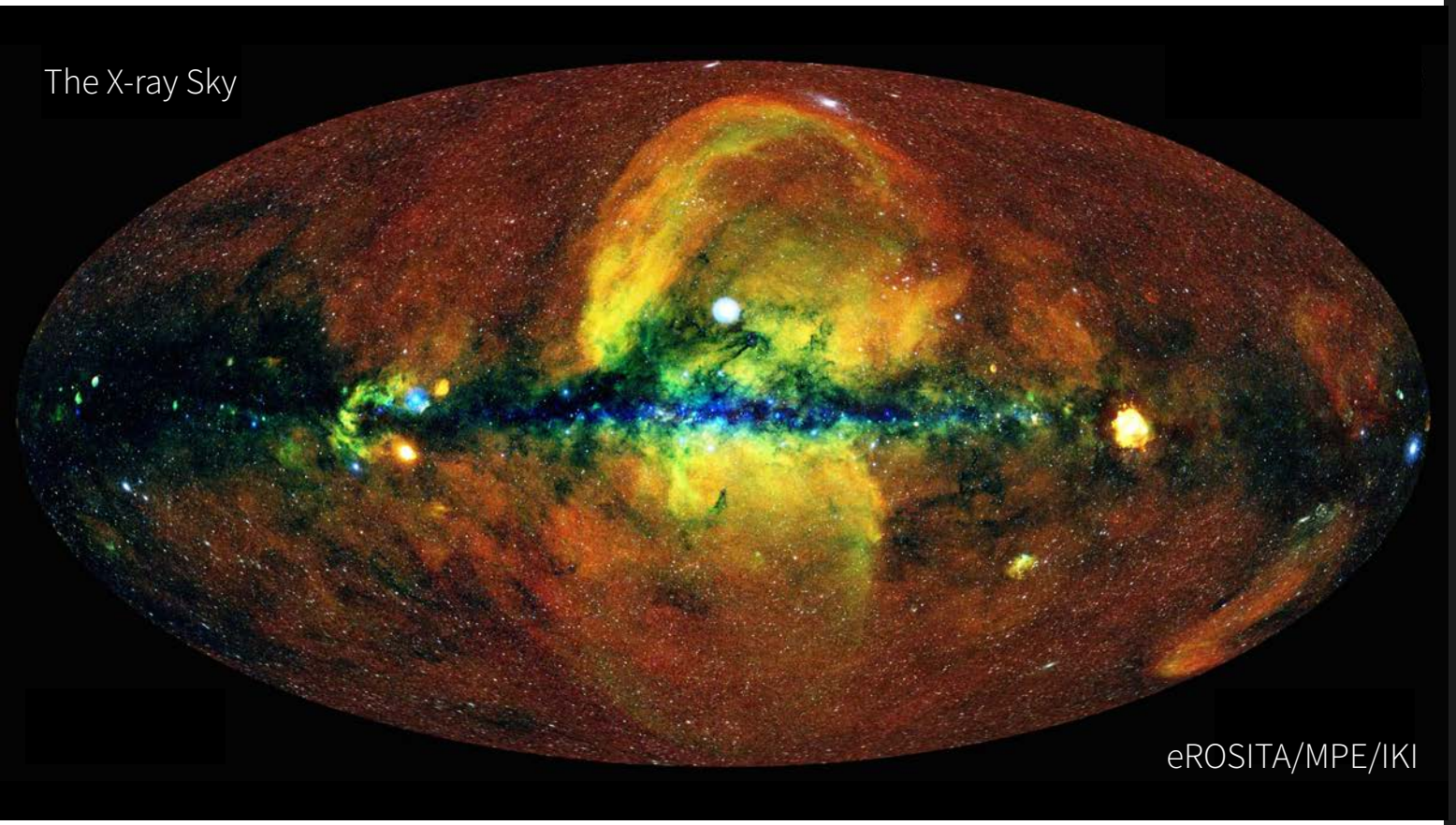
- Developed the mathematical tools to describe black holes
- Proved that once a dying star, nothing can prevent collapse to a singularity
- The cosmic censorship conjecture – all singularities (the infinitely collapsed remnants at the center) are hidden behind event horizons

Reinhard Genzel and Andrea Ghez

"for the discovery of a supermassive compact object at the center of our galaxy"

- More in the next lecture!

The X-ray sky



X-ray astronomy started in the 1960s, launching X-ray detectors on sounding rockets – detector carried to upper atmosphere, rocket spins as it flies and scans the whole sky

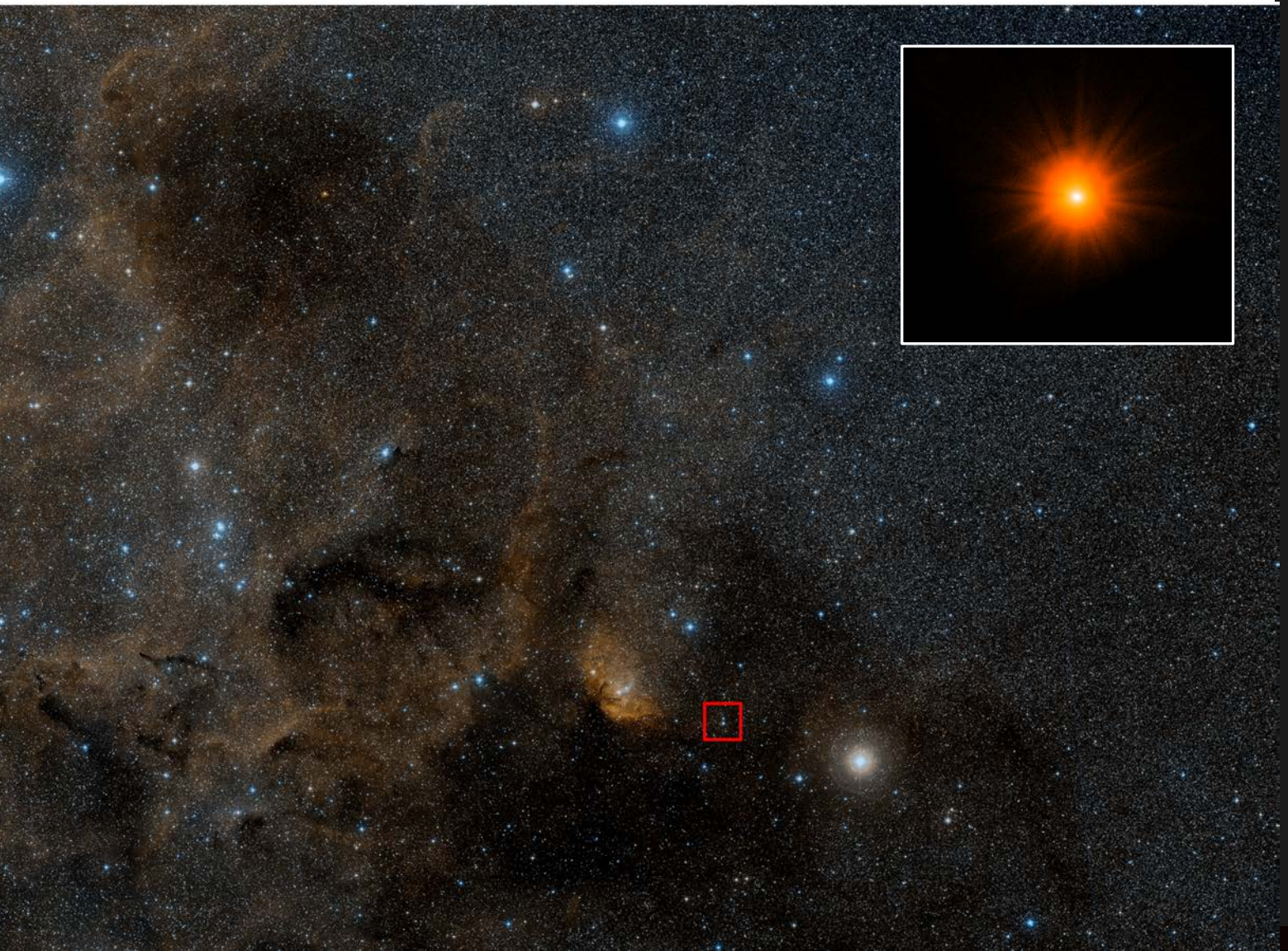
At X-ray wavelengths, the “empty sky” background is brighter than the Sun

Uhuru was the first X-ray detector on a satellite in permanent orbit (1970)

Today we have large X-ray telescopes (observatories) on satellites — Chandra, XMM-Newton, NuSTAR, eROSITA, NICER

X-ray emission isn’t smoothly spread over the sky, but comes from individual point-like sources

An X–ray star?



Bright X-ray point source discovered in constellation of Cygnus (1964)

Follow-up observations with optical telescopes revealed a massive star (15-30x mass of Sun)

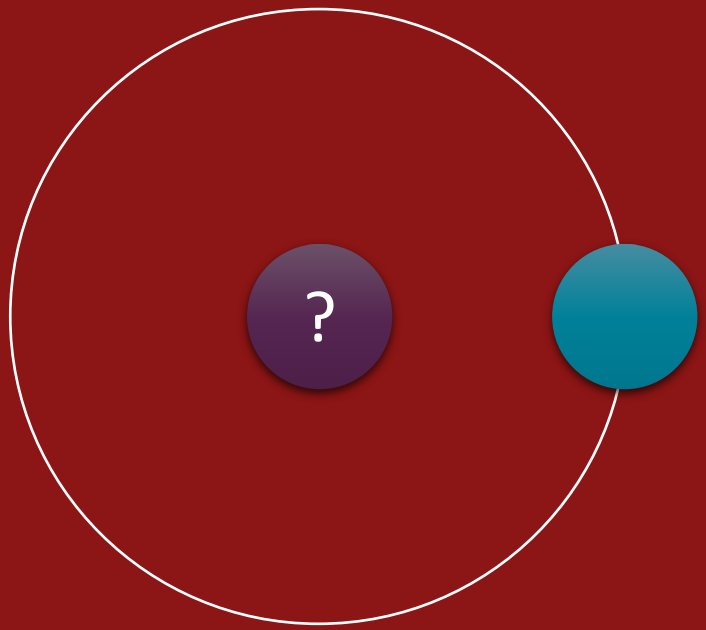
Stars shouldn’t be so bright at X-ray wavelengths WILtY

Measurements of Doppler shifts of light from the star, revealed it was orbiting an unseen companion (1971)

Q1:

The massive star (mass $20M_{\odot}$) observed at the location of Cygnus X-1 is seen to travel around an orbit with radius 0.2 AU every 5.6 days.

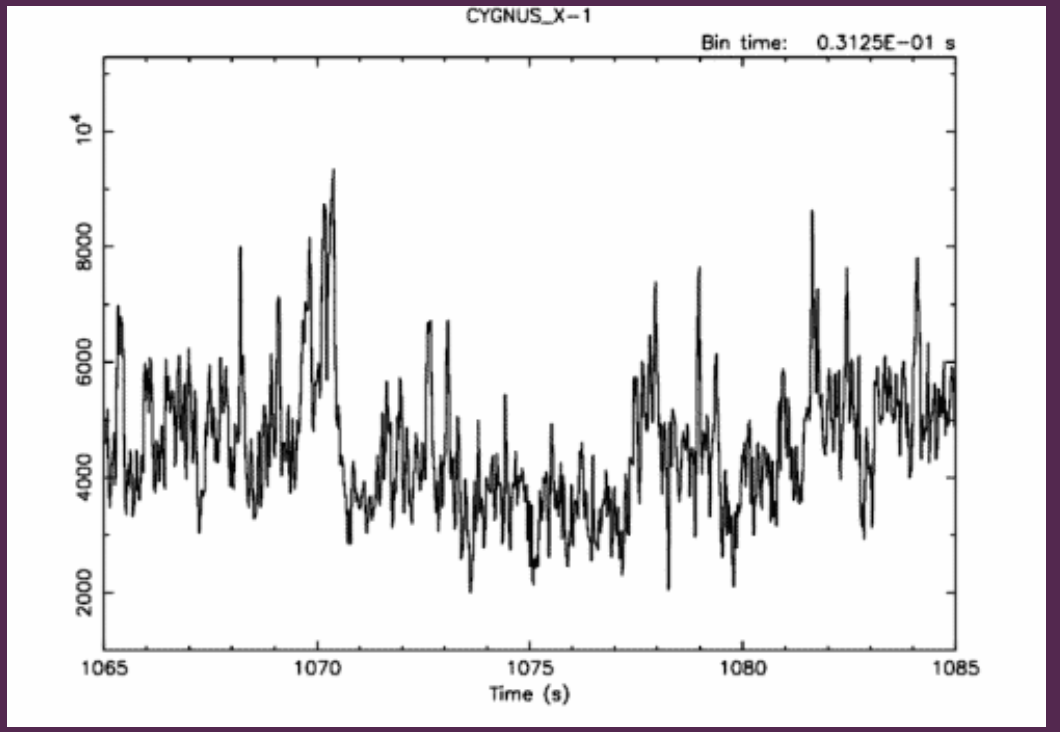
What is the mass of the unseen companion that the star is orbiting?



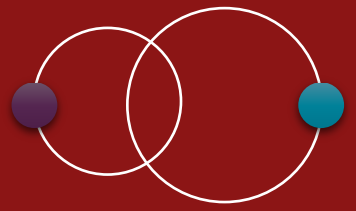
Q2:

The X-ray emission from Cyg X-1 is seen to vary rapidly. It flickers on timescales shorter than 1 ms.

Can we use this information to say anything about the size of the region the X-rays are emitted from?



The star and companion are of comparable mass, so they are in a binary orbit about one another (they orbit around their common center of mass)



Using Newton's law of gravitation, their acceleration towards each other:

$$a = \frac{G(M_1 + M_2)}{r^2}$$

For the circular orbit of the companion

$$\frac{G(M_1 + M_2)M_1}{r^2} = \frac{M_1 v^2}{r} = \frac{M_1}{r}\left(\frac{2\pi r}{P}\right)^2$$

We find that

$$(M_1 + M_2) \propto \frac{r^3}{P^2}$$ (Kepler's law)

Comparing to the Earth around the Sun, r = 1AU, P = 1yr, we find that for r = 0.2AU and P=5.6d, $M_1 + M_2 = 35M_\odot$, so the companion:

$$M_2 = 15M_\odot$$

The X-ray emission from Cyg X-1 is seen to vary rapidly. It flickers on timescales shorter than 1 ms.

For the whole object to change in luminosity together, the information about the change must travel across the object. This information cannot travel faster than the speed of light.

If the luminosity changes in less than 1ms, this means that the object is small enough that the information travelling at the speed of light can cross it in 1ms.

$$s = ct$$

We can therefore place an upper limit on the size of the region that produces the X-rays in Cyg X-1 of 300km (about half the distance from San Francisco to Los Angeles).

Many stars live in binaries

Unlike our Sun, many stars in our Galaxy are not found alone

They exist in binaries, triples or higher order systems

In a binary, 2 stars orbit each other (circular motion about their common center of mass)

One star may come to the end of its life before the other. Its remnants may collapse into a black hole

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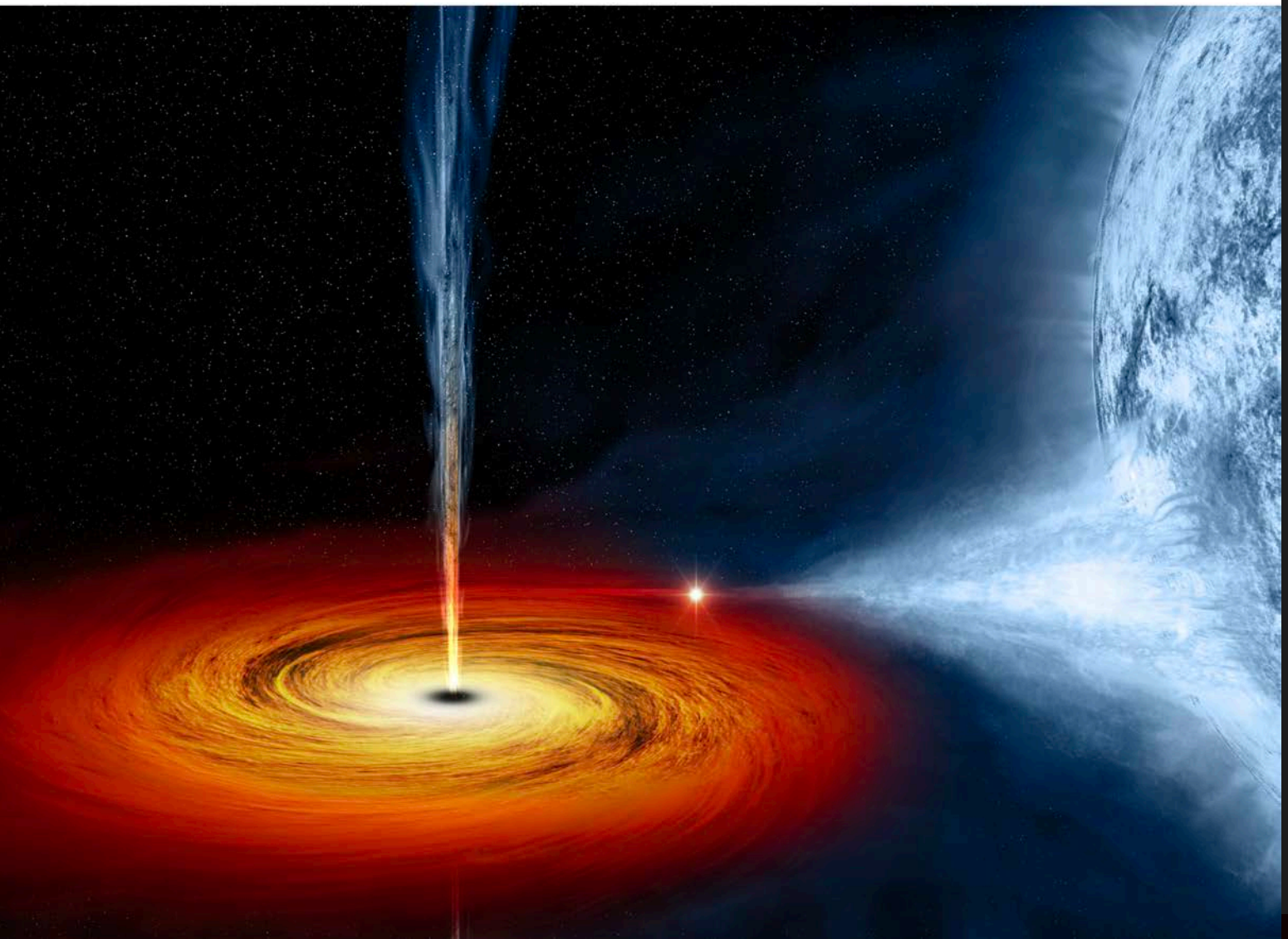
Cygnus X-1: A black hole X-ray binary



A massive star and a black hole are in a binary orbit (each pulls on the other and they orbit around their mutual center of mass)

The outer layers of gas on the star get pulled towards the black hole

This gas gets compressed and heated as it is pulled towards the black hole and reaches ~10 million degrees

We see powerful X-ray emission not from the black hole (no light can escape from the black hole itself), but from heated material as it falls towards and into the black hole

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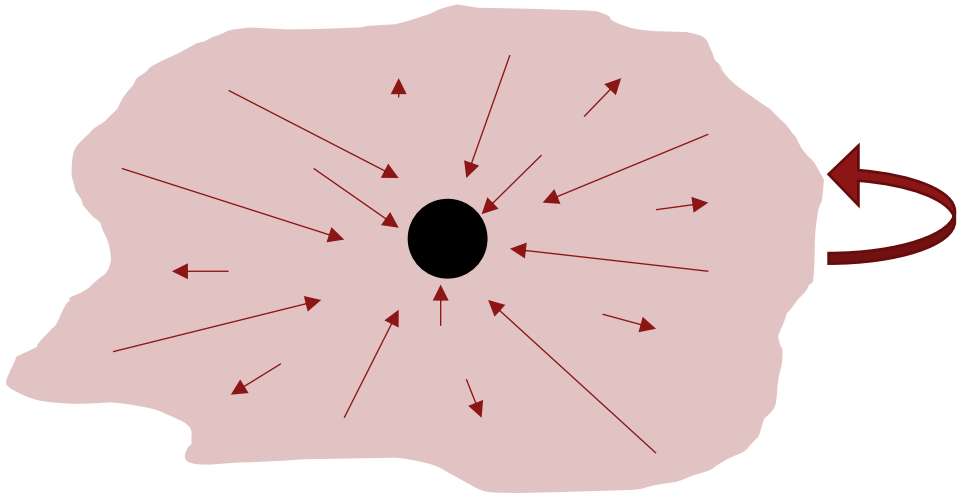
Formation of an accretion disk

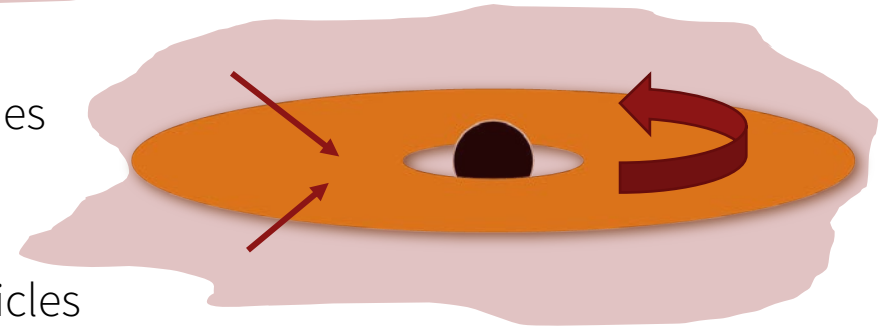


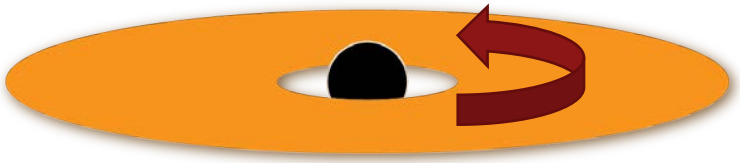
Cloud of gas collapsing towards black hole

Slight misalignment of incoming gas means it has slight rotation with respect to black hole, and has <u>angular momentum</u>

Angular momentum must be conserved, so rotation amplifies as cloud collapses

Random motion in other directions cancels out as particles collide





Gas flattens into disc orbiting the black hole

If, by random chance, the incoming gas is slightly misaligned with the black hole, as it travels it has "rotation" about the black hole

Angular momentum must be conserved:

$$J = mrv$$

As it falls in, m gets smaller so v must get larger – as a cloud of gas collapses, rotation is amplified, so close to the center, the as ends up in orbit around the black hole

On top of the rotation, there's random motion of the gas. As particles collide this motion cancels out (but can't cancel out the angular momentum), and flattens the cloud into a disc WILtY

Forms an <u>accretion disc</u> of gas working its way towards the black hole – gas travels round in orbit at each radius on the disc

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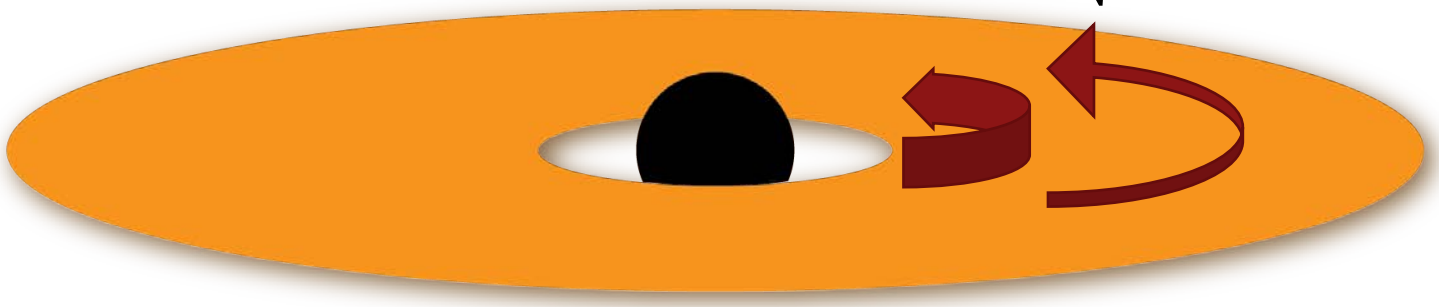
The Accretion Disk

Material at smaller radii is orbiting faster than material at larger radii

$$v = \sqrt{\frac{GM}{r}}$$



As gas rubs together, angular momentum is transferred outward

As gas loses angular momentum, it falls inward

Temperature of gas increases towards center
Emits radiation like a black body, but at 10 million deg, so emits X-rays as well as UV & visible light

At each radius in the disk, gas is on a stable, circular orbit around the black hole

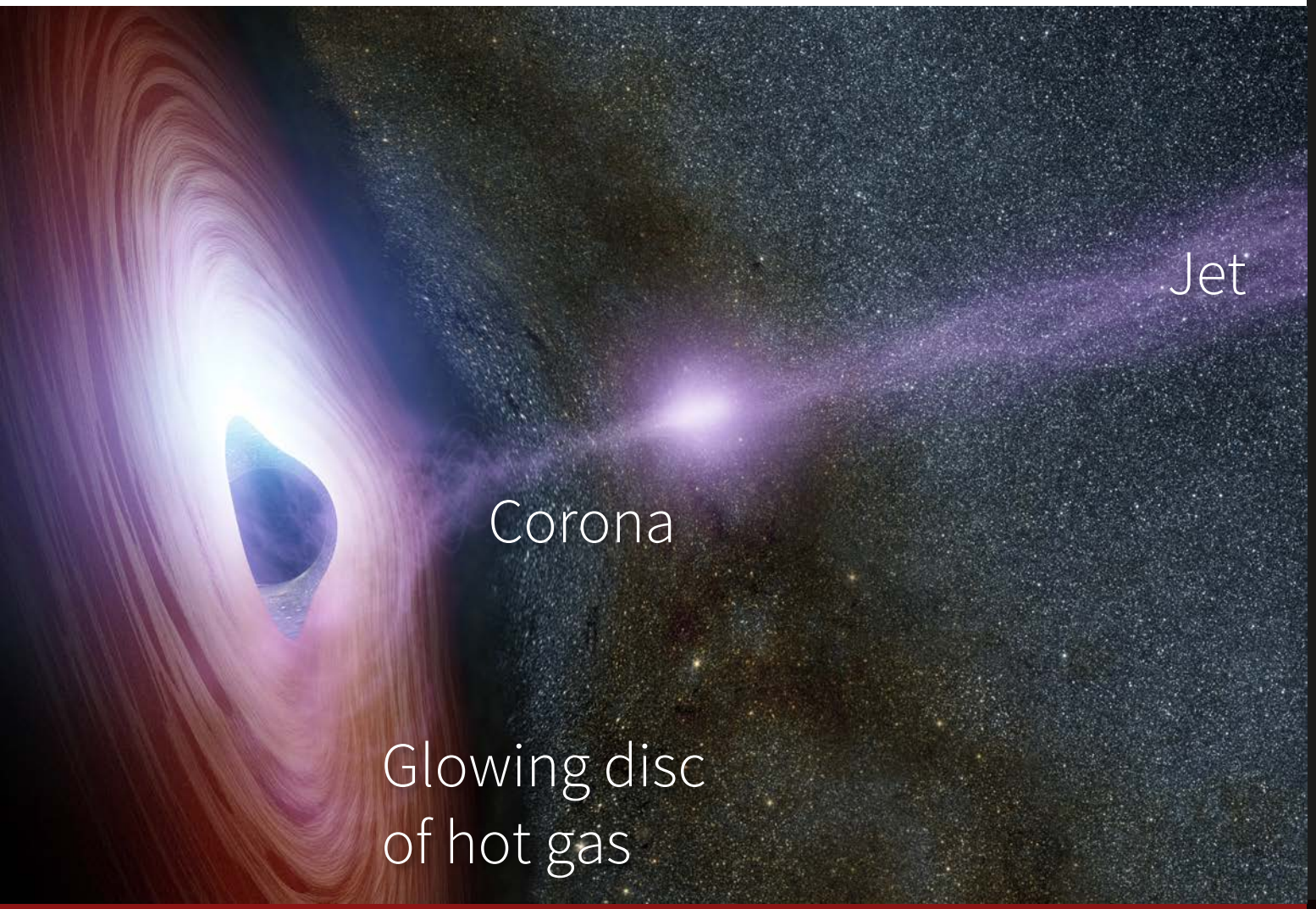
Material at smaller radii orbits faster than material at larger radii (Kepler's law)

Gas rubs together – the fast-moving inner gas drags the slow-moving gas near it and speeds it up

- Angular momentum is passed outwards
- As gas loses its angular momentum, it falls inwards
- Viscous friction as gas rubs together heats it up (normal friction is not enough, require magnetically driven friction to heat disk to observed temperature)

Gas gradually spirals in, towards the black hole, through the disk

Light from the black hole!



As gas gets compressed and heated in the accretion disk

- Each part of the disk glows, producing black body radiation
- Visible light, UV, X-ray

Accretion disk also carries magnetic fields that get twisted up as the gas orbits the black hole

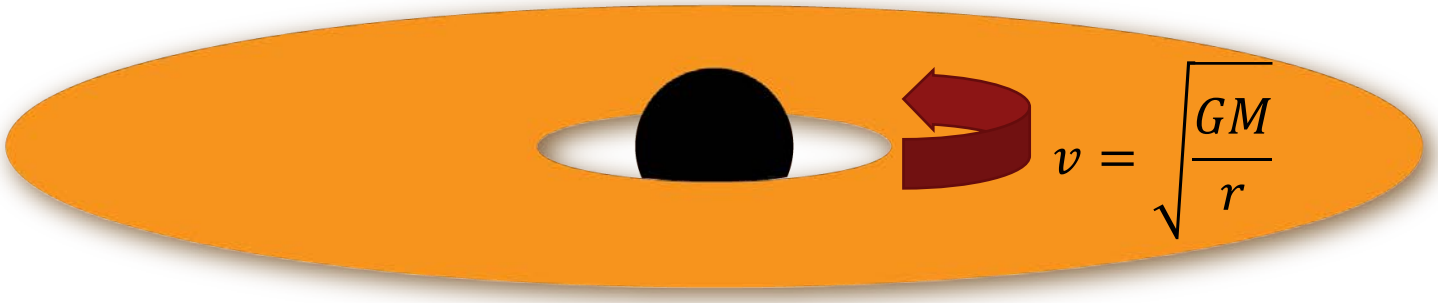
- accelerates electrons in a corona that produces X-rays that shine on the gas falling in WILtY

Magnetic fields can launch a jet of particles at close to the speed of light

No light is emitted from the black hole. We see is the hot gas falling into the black hole.

QaD

The Power Source



- A small amount of gas, mass m, begins stationary a large distance from black hole
  - Gravitational potential: $V = 0$
  - Kinetic energy: $T = 0$
  - Total energy: $E = T + V = 0$
- At $r = \frac{6GM}{c^2}$ (the minimum radius you can orbit a non-spinning black hole)
  - Gravitational potential: $V = -\frac{GMm}{r} = -\frac{1}{6}mc^2$
  - Orbital speed, $v = \sqrt{\frac{GM}{r}} = \frac{c}{\sqrt{6}}$
  - Kinetic energy: $T = \frac{1}{2}mv^2 = \frac{1}{12}mc^2$
  - Total energy: $E = T + V = -\frac{1}{12}mc^2$

When mass m falls in, $\frac{1}{12}mc^2$ energy is released as gas falls into the black hole

As gas falls into the black hole, it loses gravitational potential energy (V = 0 a large distance from the black hole and becomes more negative as it falls)

Some of this energy must become kinetic energy to keep the gas in a circular orbit (orbital speed increases at smaller radius)

The remaining gravitational potential energy is released (the gas heats up, and emits light, UV, X-rays) Bigl

In General Relativity, the minimum radius at which a stable orbit exists is $r = \frac{6GM}{c^2}$ around a non-spinning black hole ($\sim 1.235\frac{6GM}{c^2}$ if it's spinning). Within this, gravity becomes too strong. Gas plunges quickly into the black hole and most of the light it emits will fall in with it, so we assume we don't see emission from within this radius. WILtY

Mass is equivalent to stored energy $E = mc^2$

Define the efficiency, ε, the fraction of the rest mass energy that can be released

$$E = \varepsilon mc^2$$

When matter falls deep enough into a gravitational potential (i.e. onto a black hole), gravity is an extremely efficient way of releasing energy BigI

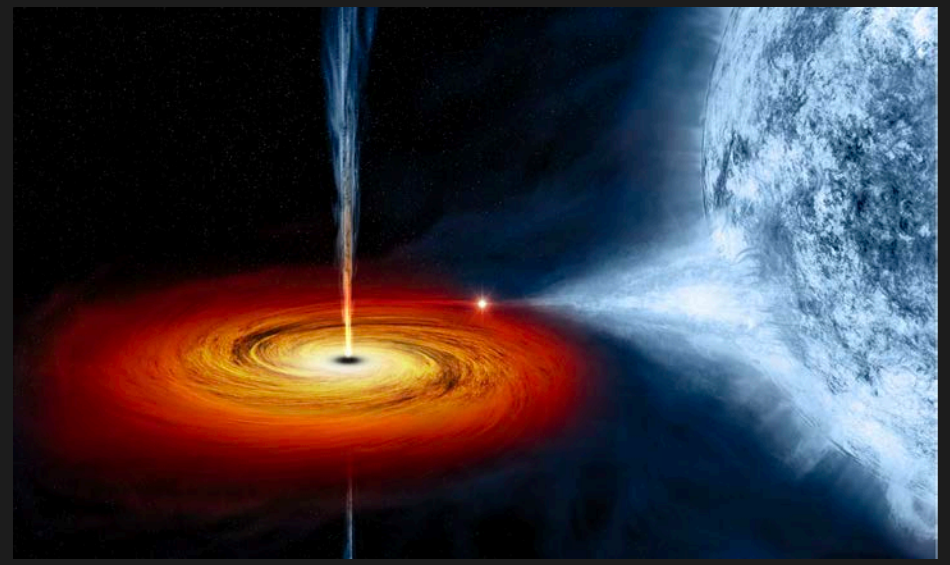
How does gravity stack up?

Process		Efficiency, ε
Chemistry (food, fires, dynamite)		0.00001%
Nuclear fission (nuclear power, nuclear bomb)		0.01%
Nuclear fusion (stars, sunlight)		0.1%
Accretion onto black holes under gravity	Newtonian	8% (incorrect for a black hole!)
	Full calculation, non-spinning black hole	6% (correct answer using relativity) WILtY
	Spinning black hole	Up to 40% (higher the more rapid the spin)

The evidence for a black hole in Cyg X-1

- Mass measured from binary orbit with stellar companion ($\sim 10 M_{\odot}$)
- Maximum size of emitting region estimated from how rapidly X-ray emission varies (no more than 100km)
- This puts it close to the Schwarzschild radius $\frac{2GM}{c^2}$
- X-ray emission as predicted from collisions of gas as it is pulled from the companion star towards the black hole (Yakov Zel'dovich, 1964)
- Emission only seen from the infalling gas (and associated processes). No emission that would be seen from the surface of a star

Louise Webster & Paul Murdin (discovery of the stellar companion to Cyg X-1, 1971)



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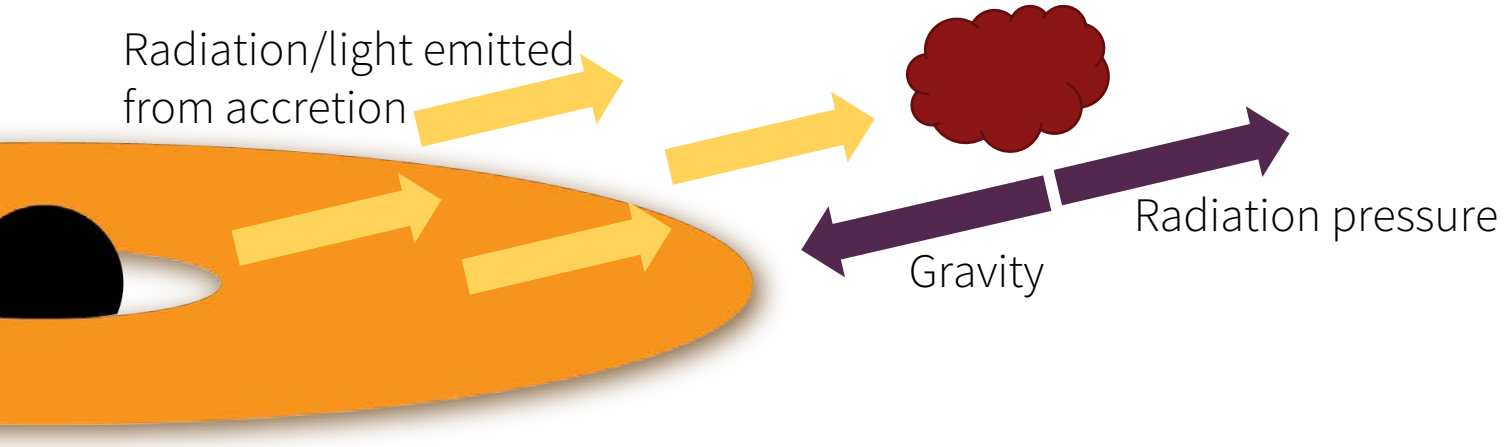
How quickly can you feed a black hole?



The Eddington limit on the luminosity (power) that can be produced by matter accreting onto a black hole:

$$L_{\mathrm{Edd}} = 10^{31}\left(\frac{M}{M_{\odot}}\right)\ \mathrm{W}$$

$\left(\frac{M}{M_{\odot}}\right)$ is the mass of the black hole in units of Solar masses

Photons carry momentum

$$p = \frac{E}{c} = \frac{h\nu}{c}$$

WILtY

Therefore, as the radiation emitted from close to the black hole reaches the gas falling in, toward the black hole, it pushes outwards — radiation pressure

If the radiation pressure is stronger than the gravitational pull, the gas gets pushed outwards and cannot fall into the black hole

The faster gas accretes (falls in) to the black hole, the more energy is released and the greater the radiation pressure

There is an upper limit on how quickly a black hole of mass M can accrete matter — the Eddington limit

(unless radiation comes out in a different direction to the inflow of matter)

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- The first discovery of an astrophysical black hole in Cygnus X-1 — mass, size estimate, compare to Schwarzschild radius, nature of X-ray emission
- Material spirals into black holes through circular orbits in an accretion disk
- Gas heats up in the accretion disk and produces a powerful light source (X-rays, UV, visible light)
- Gravity is a very efficient way of releasing energy